

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59

60

61

62

63

64

65

Review

Title: Myocardial Deformation Assessment Using

Cardiovascular Magnetic Resonance-Feature Tracking

Technique

Short Title: Cardiovascular Magnetic Resonance-Feature

Tracking Technique

1 Abstract

2 **Background:** Cardiovascular Magnetic Resonance (CMR) imaging is an important
3 modality that allows the assessment of regional myocardial function by measuring
4 myocardial deformation parameters such as strain and strain rate throughout the
5 cardiac cycle. Feature tracking is a promising quantitative post-processing technique
6 that is increasingly used. It is commonly applied to cine-images, in particular Steady
7 State Free Precession (SSFP), acquired during routine CMR examinations.

8 **Objective:** To review the studies that have used feature tracking techniques in
9 healthy subjects or patients with cardiovascular diseases (CVD). The article
10 emphasises the advantages and limitations of feature tracking when applied to
11 regional deformation parameters. The challenges of applying the techniques in
12 clinics and potential solutions are also reviewed.

13 **Results:** Research studies in healthy volunteers and/or patients either applied CMR-
14 feature tracking alone to assess myocardial motion or compared it to either
15 established CMR-tagging techniques or to speckle tracking echocardiography. These
16 studies assessed the feasibility and reliability of calculating or determining global
17 and regional myocardial deformation strain parameters. Regional deformation
18 parameters are reviewed and compared. Better reproducibility for global deformation
19 was observed compared to segmental parameters. Overall, studies demonstrated that
20 circumferential was the most reproducible deformation parameter, usually followed
21 by longitudinal strain; in contrast, radial strain showed high variability.

22 **Conclusion:** Although feature tracking is a promising tool, there are still
23 discrepancies in the results obtained using different software packages. This

1 highlights a clear need for standardisation of MRI acquisition parameters and feature
2 tracking analysis methodologies. Validation, including physical and numerical
3 phantoms, is still required to facilitate feature tracking in routine clinical practice.

4

5

1 **Keywords**

2 2 Cardiovascular magnetic resonance

3 3 Feature tracking

4 4 Tagging

5 5 Strain

6 6 Strain rate

7

1 List of abbreviations

2
3
4 2 CMR: Cardiovascular Magnetic Resonance
5

6
7 3 CMR-FT: Cardiovascular Magnetic Resonance-Feature tracking
8

9
10 4 CMR-Tagging: Cardiovascular Magnetic Resonance-Tagging
11

12
13 5 STE: Speckle tracking echocardiography
14

15
16 6 CVD: Cardiovascular diseases
17

18
19 7 STE: Speckle tracking echocardiography
20

21
22 8 SSFP: Steady state free precession
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 **Background**

2 There is a growing recognition that early detection of cardiac abnormalities could
3 improve patient quality of life and reduce both morbidity and mortality. Extensive
4 improvements and developments in CMR sequences and post-processing techniques
5 have been introduced to facilitate their use in clinical settings in order to improve the
6 diagnostic accuracy of CVD in its onset stage.

7 Recent extensive research has proven that global measures, such as ejection
8 fraction, are only an indicator of global heart function and cannot be used to infer
9 regional function, nor to detect any ventricle dysfunction at the very early stages of
10 established diseases. ¹ Contrary to visual myocardial wall-deformation analysis,
11 indices including strain, strain rate and torsion can be sensitive indicators of
12 underlying myocardial contractile dysfunctions. Those indices can be derived from
13 CMR-tagging images. ² Fig. 1 illustrates the different components of wall-
14 deformation indices relative to cardiac anatomy. Tagging sequences use spatially
15 selective saturation pulses to create dark lines on the myocardial tissue at the end
16 diastole, with those lines persisting throughout part of or all the cardiac cycle. ³
17 These techniques have since undergone extensive development and improvement for
18 both imaging sequences ^{4,5,6} and post-processing methods. ^{7,8} CMR-tagging is now
19 considered to be the gold standard for myocardial regional function assessment. ^{9,10,}
20 ¹¹

21 Feature tracking has been introduced to track myocardial motions, such as
22 displacement and velocity, and derive cardiac deformation parameters, such as strain
23 and strain rate in CMR. It tracks the tissue motion between the epicardial and
24 endocardial borders throughout the cardiac cycle using optical flow methods, see the

1 appendix for more information about feature tracking and tagging post processing
2 techniques.^{12, 13, 14} This article reviews the expanding field of feature tracking with a
3 particular emphasis on clinical and multimodality comparative studies.

4

1 **Results**

2 **Feature Tracking (CMR-FT) studies**

3 Cardiovascular Magnetic Resonance feature tracking (CMR-FT) is a quantitative
4 post-processing technique that tracks myocardial tissue motion on SSFP cine images,
5 the most commonly used sequence in clinical cardiac function assessment. The first
6 software package based on FT techniques was introduced by TomTec Imaging
7 Systems GmbH (Munich, Germany) and has been used in most clinical studies
8 published to date ^{13, 15, 16}; see Fig. 2. More recent studies used a different FT software
9 package: a tissue tracking module within the CVI42 software (Circle Cardiovascular
10 Imaging Inc. Calgary, Canada) ¹⁷; see Fig. 3. A summary of studies using CMR-FT
11 is given in Table 1.

12 Some clinical studies were dedicated to assessing the reproducibility of FT by
13 evaluating inter- and intra-observer reproducibility, whereas others applied FT to
14 both healthy subjects and patients to quantify the difference in cardiac deformation
15 parameters between those groups. ^{16, 18} Feature tracking can be applied to evaluate
16 the function and the mechanics of all heart chambers: right ventricle (RV), left
17 ventricle (LV) and atrial deformations.

18 CMR-FT was applied to detect quantitative motion changes at rest and stress of
19 LV, ^{13, 19} as left ventricular motion abnormalities detected by CMR post-processing
20 techniques could be an early and sensitive tool for any contractile dysfunction. The
21 quantitative wall parameters derived from cine images were assessed at rest and
22 during dobutamine stress in healthy volunteers ¹⁹ and in patients with ischaemic
23 cardiomyopathy. ¹³ CMR-FT demonstrated its ability to detect wall motion changes

1 between rest and stress, where circumferential and radial strains increased
2 significantly with dobutamine in both studies. However, there was no response to
3 dobutamine in dysfunctional segments with scar in patients with ischaemic
4 cardiomyopathy compared to non-dysfunctional segments. In stress studies, the more
5 reproducible myocardial deformation parameter for inter- and intra-observer was
6 circumferential strain.^{13, 19} CMR-FT can then be used to assess strain measures at
7 rest and stress and could provide a potential method for assessing wall contraction
8 changes.

9 Heart failure and cardiomyopathies have also been evaluated using CMR-FT in
10 particular hypertrophic cardiomyopathy.¹⁸ The ability of CMR-FT to differentiate
11 between patients and healthy controls was evaluated in two studies.^{15, 18} In
12 hypertrophic cardiomyopathy and heart failure patients, both left atrium longitudinal
13 strain (22.1% and 16.3 %) and strain rate (0.9 s^{-1} and 0.8 s^{-1}) were lower than in
14 healthy subjects (strain 29.1% and strain rate 1.1 s^{-1}).¹⁸ Scarred segments showed
15 lower contractile function, radial displacement, radial velocity, radial strain and
16 longitudinal strain values compared to non-scar segments. Radial strain was shown
17 to be the best parameter to discriminate between scarred segments from non-scarred
18 ones.¹⁵

19 Diseases of the aorta have also been given a great deal of attention in clinical
20 research, in particular coarctation of the aorta (COA).^{16, 20} Repaired COA patients
21 were assessed using CMR-FT compared to normal subjects.¹⁶ Global radial strain
22 and global longitudinal strain were decreased in patients, while global
23 circumferential strain was preserved compared to normal subjects. In the presence of

1 hypertrophy, global longitudinal strain was significantly reduced, which could be
2 used as an indicator of early LV dysfunction.

3 A study carried out by Maret et al. assessed the ability of the CMR-FT technique
4 to detect scar defined with gadolinium-enhanced CMR of LV.¹⁵ Scarred segments
5 showed lower functional measurements than distant segments. Myocardial function
6 can also be measured by FT-motion parameters, such as velocity and displacement of
7 a specific myocardial point or segment. Myocardial wall contractility will be reduced
8 in the presence of scar and as a consequence of reduced myocardial blood flow.

9 CMR-FT applications were not limited to cardiovascular disease patients, but
10 included healthy subjects to assess inter-study reproducibility at global and
11 segmental levels. Circumferential strain was found to be the most reproducible
12 component, as its coefficient of variation (CV) is 20.3%, whereas reproducibility for
13 radial strain was poor (CV= 27.2%).²¹ In another study, observer-variability for
14 inter- and intra- at rest was best for circumferential. observer-variability did not
15 significantly increase with stress.¹⁹

16 To evaluate whether inter-study reproducibility is affected by physiological
17 variations, sixteen healthy volunteers underwent CMR examinations 3 times on the
18 same day: the first scan was conducted after fasting, the second scan immediately
19 after the first scan, and the last examination was a non-fasting scan in the afternoon.
20 No diurnal variation was observed.²¹ Global measures showed no significant
21 difference among the three repeated scans, as opposed to segmental measures, which
22 were significant for radial strain.

23

Comparison between CMR-FT and CMR-tagging

There are currently two main CMR post-processing techniques that have been applied in order to quantify regional myocardial function: analysis of CMR tagging, and CMR-FT using functional cine images.^{18, 22, 23} Regional myocardial deformation strain is a sensitive measure for detecting onset stages of myocardial dysfunctions and can be derived from CMR-FT and CMR-tagging techniques. CMR-FT and CMR-tagging techniques can help in early identification of myocardial dysfunctions. These techniques could prove important for clinical risk management, starting treatment and helping in therapy decision-making.^{2, 24} CMR-FT is increasingly being used in studies to assess its potential in routine clinical evaluation, as CMR-FT analysis computes strain from routinely performed SSFP cine images without the need to acquire any additional CMR sequences. However, CMR-FT requires standardisation of MRI acquisition and post-processing protocols to reduce any possible discrepancies between studies beside inherent natural physiological variability between healthy subjects.²⁵ As for CMR-tagging, tagged lines fade out towards the end of the cardiac cycle making them difficult to track using post-processing techniques.²⁶ Few studies have compared CMR-FT to CMR-tagging in healthy subjects or patients to diagnose subtle myocardial motion abnormalities. The number of subjects in each study needs to be taken into account when comparisons are being made with other studies. A summary of the studies is given in Table 2.

Muscular dystrophies such as Duchenne Muscular Dystrophy were the subject of regional myocardial function assessment using both FT and tagging techniques.²⁵ The study included healthy volunteers and a large population of Duchenne Muscular Dystrophy patients of different age groups and severity; when strain values from the

1 mid-left ventricular short-axis slice were compared between the two techniques, the
2 mean circumferential strain was highly correlated. This study showed that the two
3 techniques were comparable.

4 Comparison between the two techniques was also carried out in
5 cardiomyopathies.^{11, 2, 27} One study compared the techniques in both healthy subjects
6 and hypertrophic cardiomyopathy patients.¹¹ The results showed a closer agreement
7 in time-to-peak circumferential strain than in the magnitude of strain peak between
8 both techniques. A second study compared the techniques in healthy volunteers,
9 patients with left bundle branch block and hypertrophic cardiomyopathy.²⁷ The
10 segmental peak and time-to-peak for systolic circumferential strains were assessed,
11 and both the intra- and inter-observer reproducibility were evaluated. This study
12 demonstrated that absolute values of peak systolic circumferential strain are higher
13 with CMR-FT than with tissue tagging. There was also a significant difference in
14 mean peak systolic circumferential strain values between the populations studied.
15 The inter- and intra-observer agreements were both lower with CMR-FT than with
16 tagging.

17 While most studies^{11, 25} focused solely on systolic deformation parameters, a
18 study by Moody et al.² compared both techniques in short and long axis views, both
19 in systole and diastole, in healthy subjects and patients with dilated cardiomyopathy.
20 The study showed a good agreement between CMR-FT and CMR-tagging techniques
21 for systolic global circumferential strain ($-22.7 \pm 6.2\%$ vs. $-22.5 \pm 6.9\%$, bias= 0.2
22 $\pm 4\%$, p=0.8) respectively and early diastolic global circumferential strain rate (1.21
23 $\pm 0.44 \text{ s}^{-1}$ vs. $1.07 \pm 0.3 \text{ s}^{-1}$, bias= $-0.14 \pm 0.34 \text{ s}^{-1}$). There was an acceptable agreement
24 for systolic global longitudinal strain ($-18.1 \pm 5\%$ vs. $-16.7 \pm 4.8\%$, bias= $1.3 \pm 3.8\%$,

1 p=0.03) in healthy subjects. In dilated cardiomyopathy patients, the difference
2 between both techniques was not significant ($-9.7 \pm 4.5\%$ vs. $-8.8 \pm 3.9\%$, $p=0.44$),
3 whereas the agreement for early diastolic global longitudinal strain rate was poor,
4 and the difference between both techniques was significant ($p < 0.001$) in healthy
5 subjects. Overall, there was an acceptable agreement between systolic and diastolic
6 strains for some parameters measured by both techniques in both groups. However,
7 the study only included 35 healthy subjects and 10 dilated cardiomyopathy patients;
8 this could have had an impact on the statistical results, and should be considered
9 when comparing this study to other studies with larger population sizes.

10 A different study was carried out to compare the two techniques for diastolic and
11 systolic strain measurements in patients with aortic stenosis.²⁸ In this study, the
12 strain parameters were consistently higher with FT than with tagging. Furthermore,
13 the interstudy reproducibility for circumferential peak systolic strain was excellent
14 with FT and good with tagging, whereas the reproducibility for circumferential peak
15 end diastolic strain rate was good only with basal and mid-slices.

16 Finally, FT and tagging were compared in healthy adults.²⁹ For global
17 measurement of strain, there was a good agreement between both techniques with
18 circumferential strain, but this was not the case with radial and longitudinal strains.
19 Reproducibility showed the same trends with reasonable inter-observer variability
20 for circumferential measures. The study showed some variation in strain with gender:
21 longitudinal strain values were higher in females, whereas radial values were higher
22 in males.

23 There are obvious limitations in comparison studies that could explain the
24 published disparities and disagreements in results. CMR-FT studies have been

1 published by numerous centres using heterogeneous equipment (including field
2 strength) and sequence acquisition parameters (temporal resolution, spatial
3 resolution, slice orientation etc.). All these differences can affect the reported results
4 and unfortunately, few studies include detailed limitations and reproducibility data
5 Although MRI acquisition parameters (temporal resolution, spatial resolution, slice
6 orientation etc.) could be made as close as possible for both tagging and SSFP
7 sequences, they are not identical. ^{27, 30} There were also differences in external
8 parameters such as population (population size, age, gender, heart rate, race etc.). ³¹

Comparison between CMR-FT and Echocardiography

The calculation of strain and strain rate always depends on image quality; this can have an effect on the reliability and reproducibility of deformation parameters derived from echocardiographic images. Echocardiography is limited by acquisition angle and operator dependence.^{26, 32} CMR is increasingly the method of choice because of its wide field-of-view, better image quality and reproducibility.³³ A few clinical studies have compared echocardiography and CMR-FT in patients and healthy subjects to evaluate the clinical usefulness of the latter in assessing myocardial deformation parameters.^{34, 35} A summary of studies comparing CMR-FT to echocardiography is given in Table 3.

Most comparative studies have focussed on adult congenital heart disease, in particular Tetralogy of Fallot (TOF).^{34, 36} A study was carried out in adult TOF patients and healthy subjects comparing CMR-FT to speckle tracking echocardiography (STE).³⁶ There was a close agreement between global longitudinal and circumferential LV strains measured by CMR-FT and STE techniques, but the agreement was poor for global radial LV strain. There was also a good agreement between both techniques for global longitudinal RV strain. Inter-observer agreement for both techniques was similar for LV global longitudinal strain; however, CMR-FT showed better inter-observer reproducibility for LV circumferential and radial strains and RV global longitudinal strain. There was no significant difference between TOF patients and healthy subjects in LV circumferential strain (-23.5 ± 6 vs. $-22 \pm 3.9\%$, $p=0.28$) with CMR-FT, while LV longitudinal strain (-19.2 ± 4 vs. $-21.3 \pm 3.3\%$, $p=0.048$) and LV radial strain (22 ± 8.9 vs. $28 \pm 11.3\%$, $p=0.2$) were found to be lower in patients. Furthermore, RV

1 longitudinal strain was lower in patients compared to healthy subjects (18.3 ± 4.3 vs.
2 $24.1 \pm 4\%$, $p=0.0001$).³⁶

3 The agreement between CMR-FT and STE techniques were also assessed for LV
4 and RV global longitudinal, radial and circumferential strains in TOF patients.³⁴ LV
5 global circumferential and longitudinal strains had the best inter-modality agreement,
6 whereas poorer inter-modalities and inter-observer variability were found for global
7 radial strain, contrary to what was observed for radial strain in a previous study.³⁶
8 When comparing TOF patients to healthy subjects, LV global circumferential, radial
9 and longitudinal strains and RV global longitudinal strain were lower in patients
10 compared to healthy subjects; this is in line with previously reported data.³⁶

11 The feasibility of CMR-FT technique was assessed in patients with dyssynchrony.³⁵
12 There was a reasonable agreement in radial dyssynchrony in patients with more
13 marked dyssynchrony between CMR-FT and STE. The results showed a significant
14 increase in radial myocardial contraction and circumferential strain after stent
15 implantation. The feasibility of CMR-FT technique compared to echocardiography
16 was also assessed in healthy subjects and patients with left ventricle hypertrophy
17 cardiomyopathy.³³ CMR-FT-derived strain and strain rate correlated well with
18 echocardiography, and consequently could become an alternative to
19 echocardiography for assessing myocardial deformation parameters in clinical
20 settings in the future.

Discussion

An increasing number of research studies are using feature tracking and comparing it to tagging techniques or echocardiography in both patients and healthy subjects. Some studies have proved the usefulness of feature tracking for evaluating myocardial deformation indices and differentiating between healthy and disease states. As summarised in Table 1, Table 2 and Table 3, the number of subjects vary between studies, so that comparison between those studies is affected by the number of subjects, with a subsequent impact on statistical results.³⁶ The feature tracking technique was used to assess regional cardiac function by calculating myocardial deformation parameters and their variation with age, gender and different cardiac dysfunction conditions.

The detection of motion abnormalities in the early stage of CVD is of great importance for an accurate diagnosis. Feature tracking provides a quantitative assessment of left ventricular motion,^{13, 19} and can therefore be a sensitive tool to detect contractile dysfunction. Significant changes between rest and dobutamine stress were detected by FT technique in ischaemic cardiomyopathy, with no response to dobutamine in dysfunctional parts with scar.¹³ FT can distinguish scarred segments from distant ones as scarred segments showed lower functional measures.¹⁵

Global strain measures proved to be more reproducible than regional results.^{18, 21, 34} The potential benefit of global myocardial strain assessment has been shown to be a sensitive indicator of RV function in TOF patients.³⁴ In another study that assessed inter-reproducibility in TOF patients, a close agreement was found between

1 global left (LV) and right ventricular (RV) global strain measures.³⁶ The most
2 consistently reproducible strain components were global longitudinal and global
3 circumferential strain, whereas large variations were observed in global radial strain.
4^{13, 19}

5 Despite the increasing number of published studies in feature tracking, there is
6 still an obvious lack of comparison, standardisation and validation studies.
7 Therefore, results of these studies have highlighted discrepancies between the
8 different FT software packages available. Unlike speckle tracking echocardiography,
9^{37, 38} CMR-FT has not gone through standardisation and validation in physical or
10 numerical phantom and/or animal models in order to validate it as a routine clinical
11 tool. It is of paramount importance to understand the origin of these discrepancies in
12 CMR-FT results. Consequently, in order to validate and compare the different FT
13 software, it would be ideal to develop a “ground truth” numerical phantom. Such a
14 phantom would also allow for the optimisation of clinical applications. Feature
15 tracking software providers should aim to reach a consensus for the validation and
16 standardisation of reliable deformation parameters and MRI acquisitions and analysis
17 of post-processing methods.

18

1 **Conclusion**

2 The current review summarised the main results, reproducibility, and clinical
3 applications of feature tracking studies, as well as their limitations, while also
4 suggesting important possible avenues for future work.

5 Although comparative studies with tagging and echocardiography are a necessary
6 step in validating CMR-FT, only numerical phantoms could give an absolute answer
7 when evaluating different algorithms. Ideally, synthetic images mimicking known
8 LV motions should be used to validate and compare the different FT software
9 solutions. This approach has already yielded significant results in validating speckle
10 tracking in echocardiography.³⁹ Additionally, companies offering feature tracking
11 software should be encouraged to release their algorithms to help with a scientific
12 understanding of differences between vendors and to assist in reaching a consensus
13 on the best method of analysis.³⁸ Standardising MRI acquisition parameters for FT
14 analysis will also be crucial to its wider accepted in routine clinical practice.

15

References

1. Lorca MCN, Haraldsson H, Ordovas KG. Ventricular Mechanics. *Magn Reson Imaging Clin* [Internet]. 23(1):7–13. Available from: <http://dx.doi.org/10.1016/j.mric.2014.08.005>
2. Moody WE, Taylor RJ, Edwards NC, Chue CD, Umar F, Taylor TJ, et al. Comparison of magnetic resonance feature tracking for systolic and diastolic strain and strain rate calculation with spatial modulation of magnetization imaging analysis. *J Magn Reson Imaging*. 2014/03/29. 2015;41(4):1000–12.
3. Zerhouni EA, Parish DM, Rogers WJ, Yang A, Shapiro EP. Human heart: tagging with MR imaging-a method for noninvasive assessment of myocardial motion. *Radiology*. 1988;169.
4. Axel L, Dougherty L. MR imaging of motion with spatial modulation of magnetization. *Radiology*. 1989;171.
5. Mosher TJ, Smith MB. A DANTE tagging sequence for the evaluation of translational sample motion. *Magn Reson Med*. 1990;15.
6. Fischer SE, McKinnon GC, Maier SE, Boesiger P. Improved myocardial tagging contrast. *Magn Reson Med*. 1993/08/01. 1993;30(2):191–200.
7. Kraitichman DL, Young AA, Chang CN, Axel L. Semi-automatic tracking of myocardial motion in MR tagged images. *IEEE Trans Med Imaging*. 1995;14.
8. Osman NF, Kerwin WS, McVeigh ER, Prince JL. Cardiac motion tracking using CINE harmonic phase (HARP) magnetic resonance imaging. *Magn Reson Med*. 1999;42.
9. Young AA, Axel L, Dougherty LKBD, Parenteau C. Validation of tagging with MR imaging to estimate material deformation. *Radiology*. 1993;188.
10. Edvardsen T, Gerber BL, Garot J, Bluemke DA, Lima JA, Smiseth OA. Quantitative assessment of intrinsic regional myocardial deformation by Doppler strain rate echocardiography in humans: validation against three-dimensional tagged magnetic resonance imaging. *Circulation*. 2002/07/03. 2002;106(1):50–6.
11. Harrild DM, Han Y, Geva T, Zhou J, Marcus E, Powell AJ. Comparison of cardiac MRI tissue tracking and myocardial tagging for assessment of regional ventricular strain. *Int J Cardiovasc Imaging* [Internet]. 2012;28(8):2009–18. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/22392105>
12. Hor KN, Baumann R, Pedrizzetti G, Tonti G, Gottliebson WM, Taylor M, et al. Magnetic Resonance Derived Myocardial Strain Assessment Using Feature Tracking. *J Vis Exp* [Internet]. 2011;(48):2356. Available from: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3074463/>
13. Schuster A, Paul M, Bettencourt N, Morton G, Chiribiri A, Ishida M, et al. Cardiovascular magnetic resonance myocardial feature tracking for quantitative viability assessment in ischemic cardiomyopathy. *Int J Cardiol* [Internet]. 2013;166(2):413–20. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/22130224>
14. Pedrizzetti G, Claus P, Kilner PJ, Nagel E. Principles of cardiovascular magnetic resonance feature tracking and echocardiographic speckle tracking for informed clinical use. *J Cardiovasc Magn Reson* [Internet]. 2016;18(1):51. Available from: <http://dx.doi.org/10.1186/s12968-016-0269-7>

15. Maret E, Todt T, Brudin L, Nylander E, Swahn E, Ohlsson JL, et al. Functional measurements based on feature tracking of cine magnetic resonance images identify left ventricular segments with myocardial scar. *Cardiovasc Ultrasound* [Internet]. 2009;7:53. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/19917130>
16. Kutty S, Rangamani S, Venkataraman J, Li L, Schuster A, Fletcher SE, et al. Reduced global longitudinal and radial strain with normal left ventricular ejection fraction late after effective repair of aortic coarctation: a CMR feature tracking study. *Int J Cardiovasc Imaging* [Internet]. 2013;29(1):141–50. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/22581073>
17. Almutairi HM, Zemrak F, Treibel TA, Sado D, Boubertakh R, Miquel ME, et al. A comparison of cardiac motion analysis software packages: application to left ventricular deformation analysis in hypertensive patients. *J Cardiovasc Magn Reson* [Internet]. 2015;17(1):P57. Available from: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4328428/>
18. Kowallick JT, Kutty S, Edelmann F, Chiribiri A, Villa A, Steinmetz M, et al. Quantification of left atrial strain and strain rate using Cardiovascular Magnetic Resonance myocardial feature tracking: a feasibility study. *J Cardiovasc Magn Reson*. 2014/09/10. 2014;16(1):60.
19. Schuster A, Kutty S, Padiyath A, Parish V, Gribben P, Danford DA, et al. Cardiovascular magnetic resonance myocardial feature tracking detects quantitative wall motion during dobutamine stress. *J Cardiovasc Magn Reson* [Internet]. 2011;13:58. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/21992220>
20. Lossnitzer D, Bellsham-Revell H, Bell A, Schuster A, Hussain T, Botnar RM, et al. Speckle tracking for cardiac MRI in patients pre and post dilation and stent implantation of aortic coarctation. *J Cardiovasc Magn Reson*. 2012;14(Suppl 1):P125.
21. Morton G, Schuster A, Jogiya R, Kutty S, Beerbaum P, Nagel E. Inter-study reproducibility of cardiovascular magnetic resonance myocardial feature tracking. *J Cardiovasc Magn Reson* [Internet]. 2012;14(1):43. Available from: *Journal of Cardiovascular Magnetic Resonance*
22. Taylor RJ, Umar F, Moody WE, Meyyappan C, Stegemann B, Townsend JN, et al. Feature-tracking cardiovascular magnetic resonance as a novel technique for the assessment of mechanical dyssynchrony. *Int J Cardiol*. 2014/05/24. 2014;175(1):120–5.
23. Swoboda PP, Larghat A, Zaman A, Fairbairn TA, Motwani M, Greenwood JP, et al. Reproducibility of myocardial strain and left ventricular twist measured using complementary spatial modulation of magnetization. *J Magn Reson Imaging*. 2013/09/06. 2014;39(4):887–94.
24. Donal E, Masclé S, Brunet A, Thebault C, Corbineau H, Laurent M, et al. Prediction of left ventricular ejection fraction 6 months after surgical correction of organic mitral regurgitation: the value of exercise echocardiography and deformation imaging. *Eur Heart J Cardiovasc Imaging*. 2012;13(11):922–30.
25. Hor KN, Gottliebson WM, Carson C, Wash E, Cnota J, Fleck R. Comparison of Magnetic Resonance Feature Tracking for Strain Calculation With Harmonic Phase Imaging Analysis. *JACC Cardiovasc Imaging* [Internet]. 2010;3. Available from: <http://dx.doi.org/10.1016/j.jcmg.2009.11.006>
26. Shehata ML, Cheng S, Osman NF, Bluemke DA, Lima JA. Myocardial tissue tagging with cardiovascular magnetic resonance. In: *J Cardiovasc Magn Reson*. 2009.

27. Wu L, Germans T, Guclu A, Heymans MW, Allaart CP, van Rossum AC. Feature tracking compared with tissue tagging measurements of segmental strain by cardiovascular magnetic resonance. *J Cardiovasc Magn Reson*. 2014/01/24. 2014;16:10.
28. Singh A, Steadman CD, Khan JN, Horsfield MA, Bekele S, Nazir SA, et al. Intertechnique agreement and interstudy reproducibility of strain and diastolic strain rate at 1.5 and 3 tesla: A comparison of feature-tracking and tagging in patients with aortic stenosis. *J Magn Reson Imaging*. 2015;41(4):1129–37.
29. Augustine D, Lewandowski AJ, Lazdam M, Rai A, Francis J, Myerson S, et al. Global and regional left ventricular myocardial deformation measures by magnetic resonance feature tracking in healthy volunteers: comparison with tagging and relevance of gender. *J Cardiovasc Magn Reson*. 2013/01/22. 2013;15:8.
30. Petitjean C, Rougon N, Cluzel P. Assessment of myocardial function: a review of quantification methods and results using tagged MRI. *J Cardiovasc Magn Reson*. 2005;7.
31. Moore CC, Lugo-Olivieri CH, McVeigh ER, Zerhouni EA. Three-dimensional systolic strain patterns in the normal human left ventricle: characterization with tagged MR imaging. *Radiology* [Internet]. 2000;214. Available from: <http://dx.doi.org/10.1148/radiology.214.2.r00fe17453>
32. Amundsen BH, Helle-Valle T, Edvardsen T, Torp H, Crosby J, Lyseggen E. Noninvasive myocardial strain measurement by speckle tracking echocardiography: Validation against sonomicrometry and tagged magnetic resonance imaging. *J Am Coll Cardiol* [Internet]. 2006;47. Available from: <http://dx.doi.org/10.1016/j.jacc.2005.10.040>
33. Orwat S, Kempny A, Diller GP, Bauerschmitz P, Bunck Ac, Maintz D, et al. Cardiac magnetic resonance feature tracking: a novel method to assess myocardial strain. Comparison with echocardiographic speckle tracking in healthy volunteers and in patients with left ventricular hypertrophy. *Kardiol Pol* [Internet]. 2014;72(4):363–71. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/24293146>
34. Padiyath A, Gribben P, Abraham JR, Li L, Rangamani S, Schuster A, et al. Echocardiography and cardiac magnetic resonance-based feature tracking in the assessment of myocardial mechanics in tetralogy of Fallot: an intermodality comparison. *Echocardiography* [Internet]. 2013;30(2):203–10. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/23167248>
35. Onishi T, Saha SK, Ludwig DR, Onishi T, Marek JJ, Cavalcante JL, et al. Feature tracking measurement of dyssynchrony from cardiovascular magnetic resonance cine acquisitions: comparison with echocardiographic speckle tracking. *J Cardiovasc Magn Reson* [Internet]. 2013;15:95. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/24134158>
36. Kempny A, Fernandez-Jimenez R, Orwat S, Schuler P, Bunck AC, Maintz D, et al. Quantification of biventricular myocardial function using cardiac magnetic resonance feature tracking, endocardial border delineation and echocardiographic speckle tracking in patients with repaired tetralogy of fallot and healthy controls. *J Cardiovasc Magn Reson*. 2012;14.
37. Farsalinos KE, Daraban AM, Unlu S, Thomas JD, Badano LP, Voigt JU. Head-to-Head Comparison of Global Longitudinal Strain Measurements among Nine Different Vendors: The EACVI/ASE Inter-Vendor Comparison Study. *J Am Soc Echocardiogr*. 2015/07/27. 2015;28(10):1171–81, e2.
38. Voigt JU, Pedrizzetti G, Lysyansky P, Marwick TH, Houle H, Baumann R.

- 1 Definitions for a common standard for 2D speckle tracking echocardiography:
2 consensus document of the EACVI/ASE/Industry Task Force to standardize
3 deformation imaging. Eur Hear J Cardiovasc Imaging [Internet]. 2015;16. Available
4 from: <http://dx.doi.org/10.1093/ehjci/jeu184>
- 5 39. D'Hooge J, Barbosa D, Gao H, Claus P, Prater D, Hamilton J, et al. Two-dimensional
6 speckle tracking echocardiography: standardization efforts based on synthetic
7 ultrasound data. Eur Hear J - Cardiovasc Imaging [Internet]. 2015; Available from:
8 [http://ehjcmaging.oxfordjournals.org/content/ejechocard/early/2015/08/17/ehjci.jev1](http://ehjcmaging.oxfordjournals.org/content/ejechocard/early/2015/08/17/ehjci.jev197.full.pdf)
9 [97.full.pdf](http://ehjcmaging.oxfordjournals.org/content/ejechocard/early/2015/08/17/ehjci.jev197.full.pdf)
- 10 40. Abraham TP, Dimaano VL, Liang HY. Role of tissue Doppler and strain
11 echocardiography in current clinical practice. Circulation. 2007/11/28.
12 2007;116(22):2597–609.
- 13
14

1 **Figure legends**

2 **Figure 1:** Myocardial deformation contains three strain components, circumferential,
3 radial and longitudinal of the left ventricle: longitudinal (A), radial and
4 circumferential (B). The direction of the deformation in diastole is shown as a dashed
5 line and in systole shown as a solid line. The myocardial fibres shorten and lengthen
6 in the three spatial directions: longitudinal, radial and circumferential. The strain can
7 be calculated as the difference between myocardial fibre length (radial,
8 circumferential and longitudinal) at end-diastole and at end-systole divided by the
9 length at end-diastole, and expressed as percentage (%).⁴⁰

10 **Figure 2:** Example of FT analysis using Tomtec. Endocardial and epicardial
11 contours of the LV are drawn on one frame and propagated throughout the cardiac
12 cycle. (a) A short axis slice with endocardial and epicardial contours (left-hand side),
13 and the corresponding radial (upper right-hand side) and circumferential strains
14 (lower right-hand side). (b) A 2-chamber view with endocardial and epicardial
15 contours (left-hand side), with corresponding radial (upper right-hand side) and
16 longitudinal strains (lower right-hand side). (c) A 4-chamber view with endocardial
17 and epicardial contours (left-hand side), and the corresponding radial (upper right-
18 hand side) and longitudinal strains (lower right-hand side). Other deformation
19 parameters such as velocity, displacement and strain rates can be calculated.

20 **Figure 3:** Example of CVI42 FT analysis. The software semi-automatically defines
21 the endocardial (red contour) and epicardial (green contour) LV contours throughout
22 the cardiac cycle. (a) A short axis slice with delineated endocardial and epicardial
23 contours (left-hand side) and the corresponding radial (middle) and circumferential
24 strains (right-hand side). (b) A 2-chamber long axis slice with delineated endocardial

1 and epicardial contours (left-hand side) and the corresponding radial (middle) and
2 longitudinal strains (right hand side). (c) A 4-chamber long axis slice with delineated
3 endocardial and epicardial contours (left hand side) and the corresponding radial
4 (middle) and longitudinal strains (right hand side). Additional calculated parameters
5 include velocity, displacement and strain rates.

6

7

Table 1: Comparison between studies using CMR-FT technique

Study	Strain parameters	Software	Healthy subjects	Subjects Disease studied	Main findings		Limitations
					Positive	Negative	
Schuster et al., 2011 ¹⁹	RV & LV C, R, L Segmental, Global	Tomtec	10	-	- During dobutamine stress, CS & RS increased significantly. - CS, Best observer variability of LV.	- Worse observer variability of RV-LS.	- Small sample size.
Schuster et al., 2013 ¹³	LV C, R Segmental	Tomtec CVI42	-	15 Ischaemic cardiomyopathy	- No response to dobutamine in dysfunctional segments with scar in all C & R strain parameters.		- Small sample size. - No Follow up post-revascularization data. - No functional recovery data.
Kowallick et al., 2014 ¹⁸	LA L Global and segmental	Tomtec	10	20 Hypertrophic cardiomyopathy (10) Heart failure (10)	- Excellent inter- & intra-observer variability for all strain and SR. - LS discrimination between patients and healthy controls.		- Small sample size.
Taylor et al., 2014 ²²	LV C, R Segmental	Tomtec	55	108 Cardiomyopathy	- Lower CS & RS in patients than healthy controls.		- Heterogeneous age and gender groups.
Maret et al., 2009 ¹⁵	LV R, L Global and segmental	Tomtec	-	30 Presence of LV scar	- Lower functional measures in scarred segments than distant segments.		- Heterogeneous related to gender. - A large number of infarctions with subendocardial distribution is needed to be tested by the FT-technique. - Low accuracy of ejection fraction.
Morton et al., 2012 ²¹	LV R, L Global and segmental	Tomtec	16	-	- More reproducible for global measurements than segmental ones. - CS most reproducible measure of LV.	- Variable inter-study reproducibility. - L measures least reproducible segmental measure of RV measurements. RS least reproducible global measurement.	- Small sample size.

C= Circumferential, R= Radial, L= Longitudinal, CS= Circumferential strain, RS= Radial strain, LS= Longitudinal strain, CSR= Circumferential strain rate, GRS= Global radial strain, GLS= Global longitudinal strain, GCS= Global circumferential strain, LV= Left ventricle, RV= Right ventricle, LA= Left atrial.

Tomtec= (TomTec Imaging Systems, Munich, Germany). CVI42= CVI42 (Circle Cardiovascular Imaging Inc. Calgary, Canada).

Table 2: Comparison between studies using CMR-FT and tagging techniques

Study	Strain parameters	Software	Healthy subjects	Subjects Disease studied	Main findings		Limitations
					Positive	Negative	
Hor et al., 2010 ²⁵	LV C Global and segmental	TomTec HARP	42	19 Duchenne Muscular Dystrophy (DMD)	- CS derived by FT highly correlated with tagging technique. - Low intra-observer and inter-observer bias and variability for FT.		- Analysis only performed on a mid-left ventricular short axis slice. - Only average strain was calculated, regional measures were not included in the study.
Harrild, D.M et al. 2009 ¹¹	LV C		13	11 Hypertrophic cardiomyopathy	- Close agreement between both techniques. - Better agreement for time to peak strain than peak strain magnitude.		- Small sample size. - Endocardial circumferential strain from mid-left ventricle was the only examined parameter. - Further study needed to examine radial and longitudinal strains as well as epicardial strain.
Augustine et al. 2013 ²⁹	C, R, L Global and segmental	TomTec CIMTag2D	145	-	- Good agreement between both techniques for CS. - Acceptable global inter-observer variability for circumferential measures. - Some variation in strain with gender: longitudinal strain higher and radial lower in females.	- Poor agreement between FT and tagging for R and LS. - Poor inter-observer reproducibility for R and LS for both techniques.	- Healthy subjects were heterogeneous related to gender.
Singh et al., 2014 ²⁸	C, L Global and segmental	TomTec InTag	-	18 aortic stenosis (AS)	- Excellent inter study reproducibility for circumferential peak systolic strain with FT and good with tagging. - Good reproducibility for circumferential peak end diastolic strain rate for basal and mid slices only.	- Strain parameters consistently higher with FT.	- Small sample size.
Wu et al., 2014 ²⁷	LV C Segmental	TomTec MASS	10	20 left bundle branch block (10) hypertrophic cardiomyopathy (10)		- Intra and inter-observer agreement of segmental peak SCS and T2P-SCS substantially lower with FT compared with tagging. - Significant differences in mean peak SCS values between FT and tagging. - Higher absolute values of peak SCS with FT compared with tagging. - Significant difference in mean peak SCS values.	- Small sample size. - Similar but not identical slice level used for CMR-FT and CMR-tagging.
Moody et al., 2014 ²	LV C, L Global	TomTec CIMTag2D	35	10 dilated cardiomyopathy	- Good agreement between both techniques at peak global systolic circumferential strain and early global diastolic circumferential strain rate. - Acceptable agreement at peak systolic global longitudinal strain.	- Poor agreement for early diastolic global longitudinal strain.	- Small sample size. - As a result of tag fading, late diastolic strain measures not possible.

C= Circumferential, R= Radial, L= Longitudinal, CS= Circumferential strain, RS= Radial strain, LS= Longitudinal strain, SCS= Systolic circumferential strain, T2P-SCS= Time-to-peak-systolic circumferential strain, LV= Left ventricle.

15
16 Tomtec= MR FT analysis (TomTec Imaging Systems, Munich, Germany). Tagging analysis: HARP= (Diagnosoft, Palo Alto, California). CIMTag2D= (CIMTag2D v.7, Auckland MRI Research Group, New Zealand). InTag=
17 (Creatis, Lyon, France) and MASS= (Medis, Leiden, The Netherlands).
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 3: Comparison between studies using CMR-FT and echocardiography

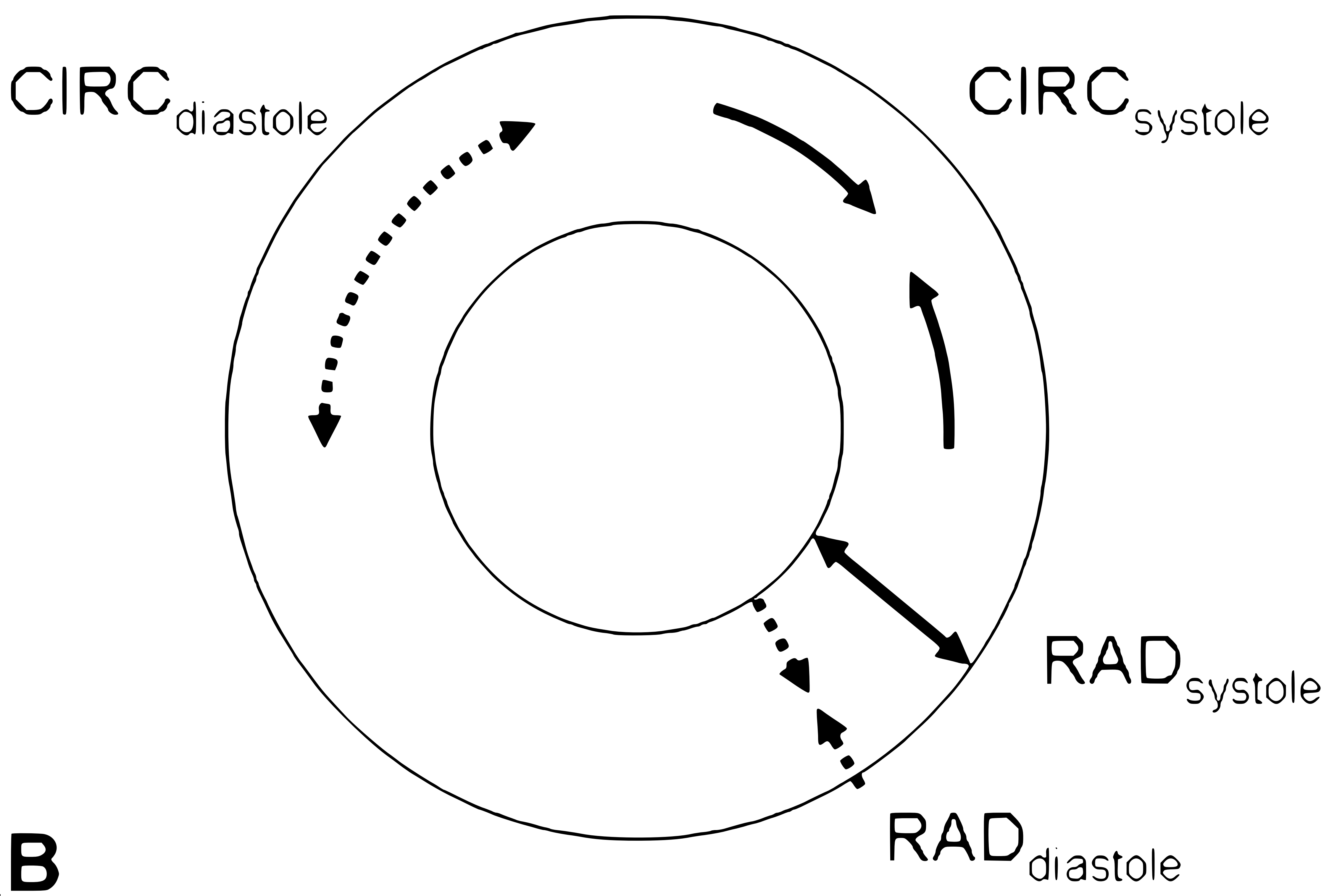
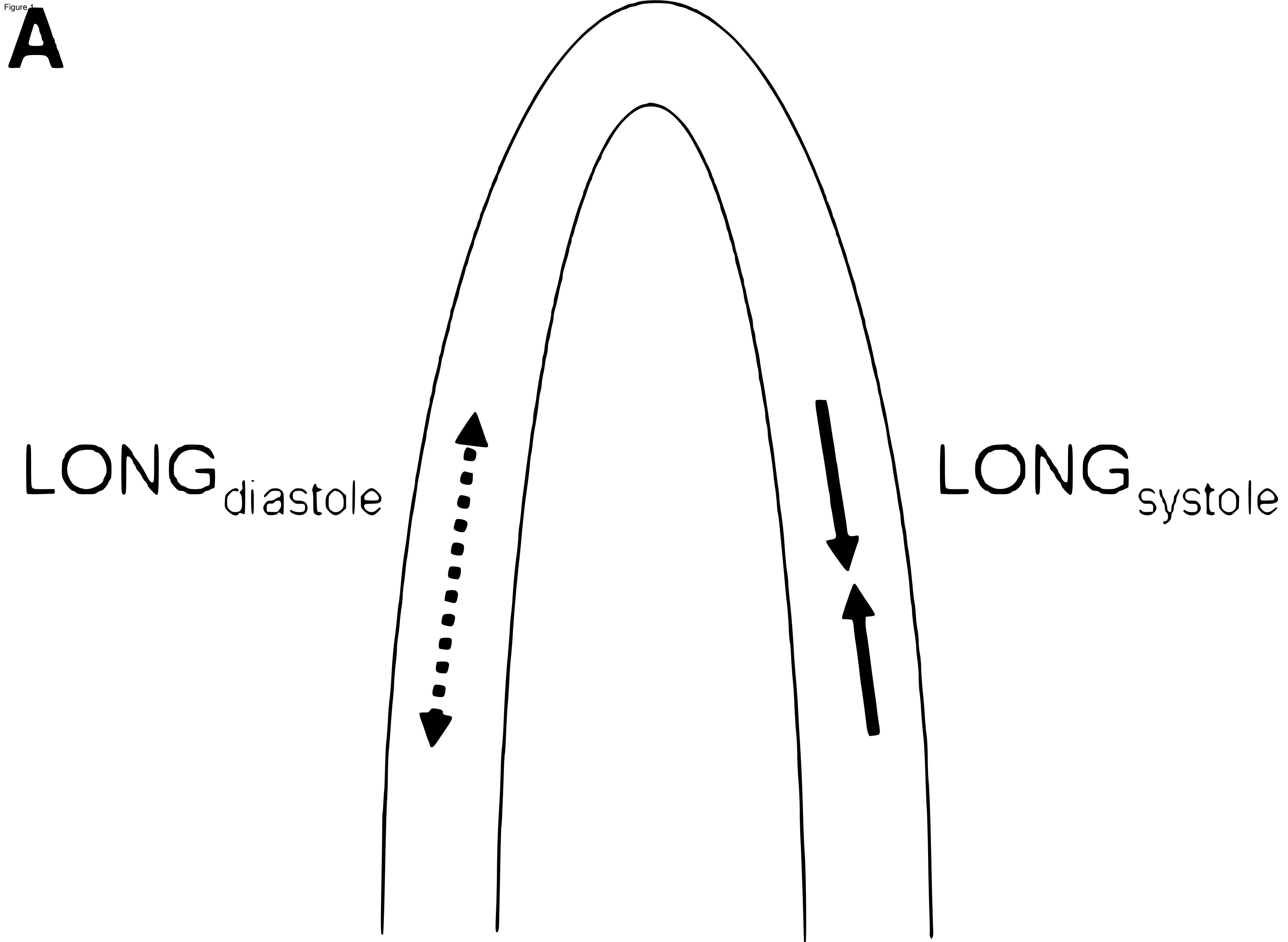
Study	Strain parameters	Software	Healthy subjects	Subjects Disease studied	Main findings		Limitations
					Positive	Negative	
Kempny et al., 2012 ³⁶	RV & LV C, R, L Global and segmental	TomTec Tomtec (STE)	25	28 Tetralogy of Fallot	- Close agreement between global LV and global RV strain measurements. - Similar inter-observer agreement for both modalities for LV GLS. - Better inter-observer reproducibility for LV CS or RS and RV GLS measured by FT.	- Reproducibility for regional strain using FT technique was poor.	- No TOF patients with different severity of pulmonary regurgitation data, for the association between the severity of pulmonary regurgitation and strain measurements.
Padiyath et al., 2013 ³⁴	RV & LV C, R, L Global and segmental	TomTec Tomtec (2DE)	20	20 Tetralogy of Fallot	- Best intermodality agreement for GCS followed by GLS. - Acceptable inter-observer agreement for GLS and GCS of LV and RV with both modalities.	- Inter-modality and inter-observer agreements were poor for GRS.	- Small sample size. - Heterogeneous related to age and gender in both groups. - No Right ventricle out flow assessment by FT technique.
Onishi et al., 2013 ³⁵	R Segmental	TomTec Tomtec		72 Dyssynchrony	- Reasonable agreement between both modalities for the patients with more marked dyssynchrony.		- No available long term follow up data.
Orwat et al., 2014 ³³	L, C Global	TomTec Tomtec	20	20 patients with left ventricular hypertrophy cardiomyopathy (HCM)	- Good agreement between both modalities for LV GLS for healthy and patients.	- Poor agreement for CS and all SR measurements. - Higher LV and RV strain, inter-observer reproducibility compared to SR.	- Small sample size. - Heterogeneous related to age in both group.

C= Circumferential, R= Radial, L= Longitudinal, CS= Circumferential strain, RS= Radial strain, LS= Longitudinal strain, CSR= Circumferential strain rate, GRS= Global radial strain, GLS= Global longitudinal strain, GCS=Global circumferential strain, LV= Left ventricle, RV= Right ventricle.

Tomtec= MR feature tracking analysis. Echocardiography FT: Tomtec (2DE) = 2D Echocardiography analysis. Tomtec (STE)= Speckle Tracking analysis. (TomTec Imaging Systems, Munich, Germany).

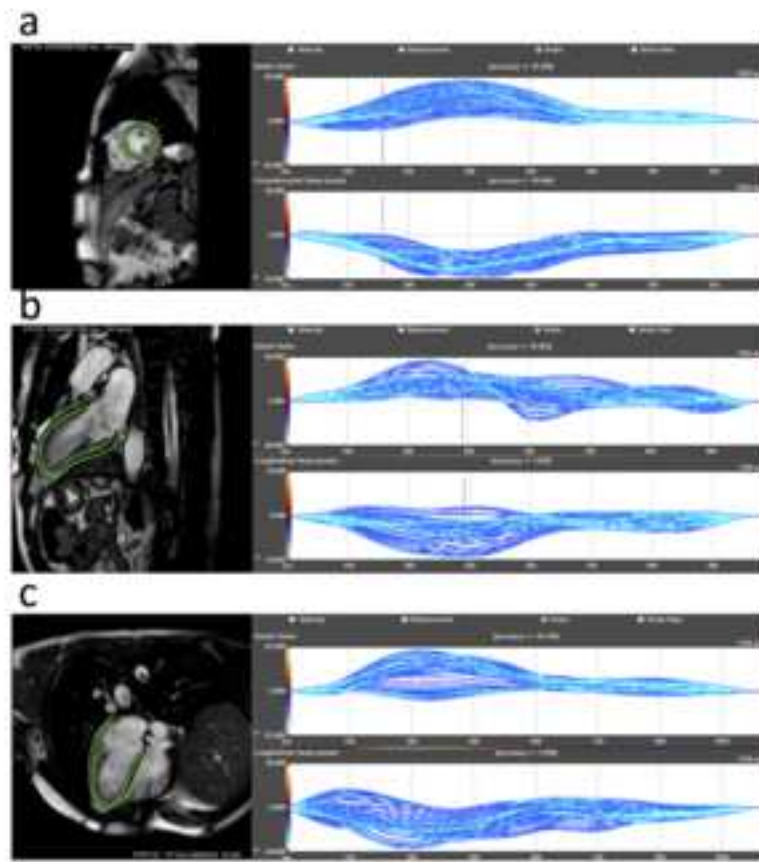
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

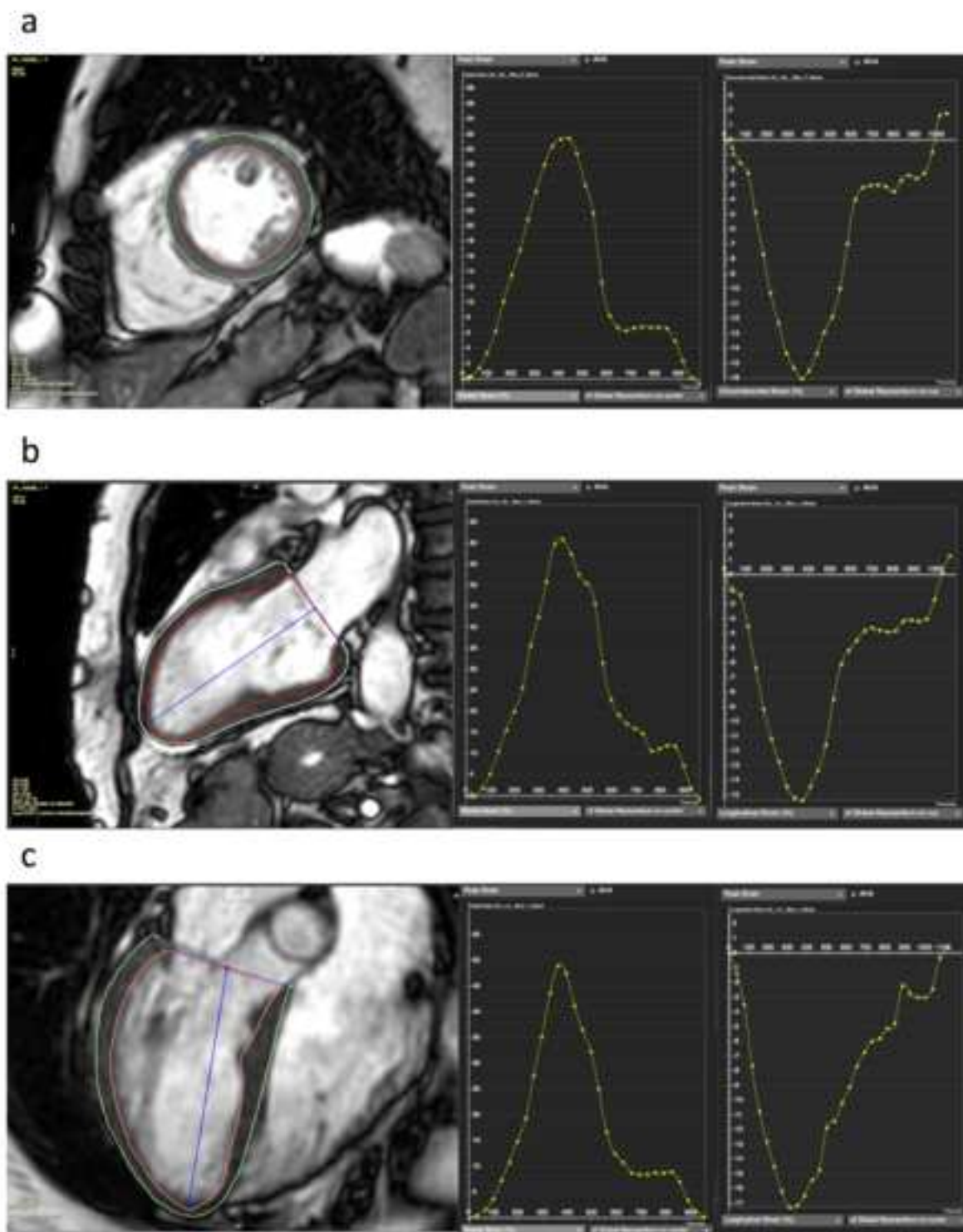
A



B

Figure 2





Appendix

A1: CMR Tagging

The first CMR-tagging sequence was introduced in the late eighties by Zerhouni.¹ CMR-tagging is based on applying spatially selective saturation pulses perpendicular to the imaging plane, which cause a saturation of the magnetisation along one (line tagging) or two (grid tagging) spatial directions. The intersection of the selected slice and imaging plane create visible dark lines (low signal intensity) on the myocardial tissue before image acquisition. CMR-tagging acquisition sequences have since undergone extensive development and improvements.^{1,2} Different post-processing techniques exist to extract and track myocardial tagging lines' deformation from consecutive frames and calculate local and global parameters such as displacement or velocity throughout the entire cardiac cycle.³ The most common CMR-tagging post processing approaches are listed below.

1) Active contour: This semi-automated method, introduced in 1994⁴, uses an active shape model that delineates the image contours in a region of interest in the LV. A deformable spline is constrained by image forces which pulls it iteratively towards the LV and tagged lines' contours until the delineating contour matches the LV boundaries or tagged lines.⁵

2) Optical flow: This method determines motion by tracking and detecting the displacement vector (image velocity) of the different image signal intensities and image features (tagged and non-tagged tissues) as they move throughout the cardiac cycle.⁶ Myocardial deformation is calculated from the corresponding 2D motion field.

3) Sinusoidal Analysis: This method extracts motion from CMR-tagging images based on a sinusoidal approach. Image intensity distribution of each pixel in the tagging image is modelled as a moving sine wave with local frequency and amplitude. The displacement is assessed at subpixel accuracy, making it highly accurate.⁷

4) Volumetric modelling: To allow three-dimensional detection of the tagged lines, a set of tagged short-axis and long-axis slices are used to compute 3D myocardial deformation and rotation parameters.⁸

5) Finite element modelling: This method reconstructs 3D myocardial motion from CMR-tagging images without prior detection of the boundaries and tagging lines locations. A model is used to define the heart shape and motion. Model tagging points are generated as a material surface, which defines the location of the tagged lines. The difference between the model tagging points and images' tagging lines is extracted and minimised to allow the model to deform the images tagging lines.⁹

A2: Feature tracking

In 2011, the CMR-FT technique was introduced as a quantitative post-processing technique for cine SSFP sequences that are acquired as part of routine clinical cardiac examinations.¹⁰ The fundamental principle of the feature tracking method is based on optical flow to extract spatiotemporal image features, such as varying image signal intensities, local textures and patterns from the cine images. The technique can then track anatomical features, such as epicardial and endocardial borders and myocardial tissue, in consecutive cine image frames by searching for the most comparable features in a local neighbourhood (defining a local voxel search window).

Current FT software packages are semi-automated and rely on an operator to manually delineate the initial endocardial and epicardial contours, usually on the end-diastolic cardiac phase. This frame then serves as the initial time point from which all motion parameters are calculated. Myocardial deformation parameters such as displacement, velocity, strain and strain rates can be computed at local and global levels.¹¹

FT was initially developed for 2D cine images but can easily be extended to 3D cine images based on the same principles. The details of how tracking is implemented in different FT-software packages are not always known and this might affect the quality and accuracy of the tracking and of the derived strain measurements. Furthermore, results are also affected by CMR imaging sequence parameters, such as temporal and spatial resolutions, and image quality, in particular signal-to-noise ratio.

References

1. Zerhouni EA, Parish DM, Rogers WJ, Yang A, Shapiro EP. Human heart: tagging with MR imaging--a method for noninvasive assessment of myocardial motion. *Radiology* [Internet]. 1988;169. Available from: <http://dx.doi.org/10.1148/radiology.169.1.3420283>
2. Moody WE, Taylor RJ, Edwards NC, Chue CD, Umar F, Taylor TJ, et al. Comparison of magnetic resonance feature tracking for systolic and diastolic strain and strain rate calculation with spatial modulation of magnetization imaging analysis. *J Magn Reson Imaging*. 2014/03/29. 2015;41(4):1000–12.
3. Mosher TJ, Smith MB. A DANTE tagging sequence for the evaluation of translational sample motion. *Magn Reson Med* [Internet]. 1990;15(2):334–9. Available from: <http://dx.doi.org/10.1002/mrm.1910150215>
4. Guttman MA, Prince JL, McVeigh ER. Tag and contour detection in tagged MR images of the left ventricle. *IEEE Trans Med Imaging*. 1994;13.
5. Guttman MA, Zerhouni EA, McVeigh ER. Analysis of cardiac function from MR images. *IEEE Comput Graph Appl*. 1997;17.
6. Barron JL, Fleet DJ, Beauchemin SS. Performance of optical flow techniques. *Int J Comput Vis* [Internet]. 1994;12. Available from: <http://dx.doi.org/10.1007/BF01420984>
7. Arts T, Prinzen FW, Delhaas T, Milles JR, Rossi AC, Clarysse P. Mapping displacement and deformation of the heart with local sine-wave modeling. *IEEE Trans Med Imaging*. 2010;29.
8. O'Dell WC, Moore CC, Hunter WC, Zerhouni EA, McVeigh ER. Three-dimensional myocardial deformations: calculations with displacement field fitting to tagged MR images. *Radiology*. 1995;195.
9. Young AA. Model tags: direct three-dimensional tracking of heart wall motion from tagged magnetic resonance images. *Med Image Anal*. 1999;3.
10. Hor KN, Baumann R, Pedrizzetti G, Tonti G, Gottliebson WM, Taylor M, et al. Magnetic Resonance Derived Myocardial Strain Assessment Using Feature Tracking. *J Vis Exp* [Internet]. 2011;(48):2356. Available from: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3074463/>
11. Pedrizzetti G, Claus P, Kilner PJ, Nagel E. Principles of cardiovascular magnetic resonance feature tracking and echocardiographic speckle tracking for informed clinical use. *J Cardiovasc Magn Reson* [Internet]. 2016;18(1):51. Available from: <http://dx.doi.org/10.1186/s12968-016-0269-7>